Atmospheric monitoring and inverse modelling for verification of GHG inventories

Current Space-based Capabilities and Prospects for Verifying CO_2 Emission Inventories and Other Anthropogenic CO_2 Emissions on National Scales

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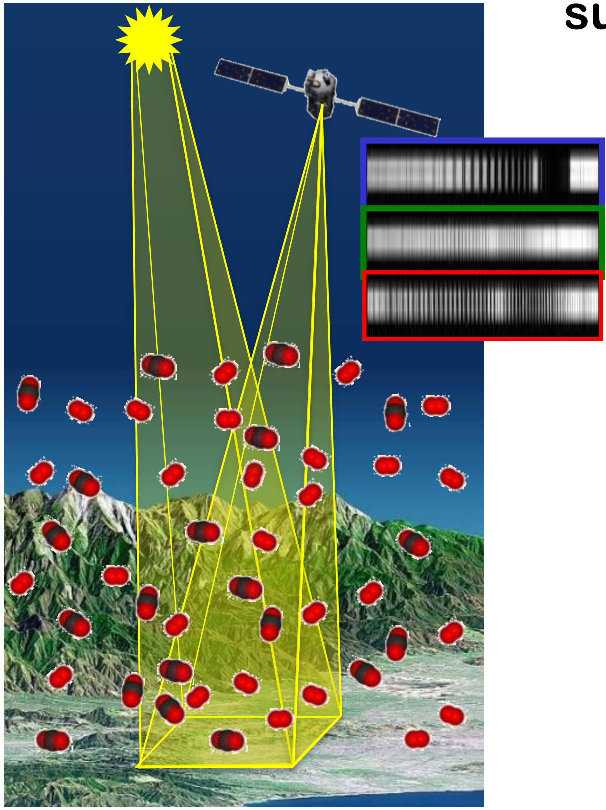
Estimating Fluxes from Space-based CO_2 Measurements

Estimating surface fluxes of CO_2 or CH_4 from space-based observations of reflected sunlight is a 6-step process:

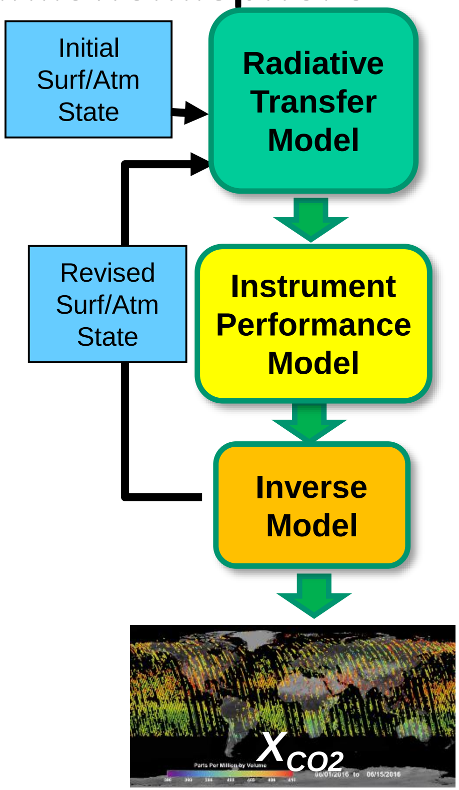
1. Acquire high spectral resolution, co-bore-sighted observations within near infrared CO_2 and O_2 bands at high spatial resolution over the sunlit hemisphere
2. Calibrate these measurements to yield spectral radiances
3. Use remote sensing retrieval algorithms to estimate the column-averaged CO_2 and CH_4 dry air mole fractions, X_{GHG}, and other state properties from each sounding
4. Validate the X_{GHG} estimates against available standards
5. Perform a flux inversion to estimate the surface GHG fluxes needed to maintain the observed X_{GHG} distribution in the presences of the prevailing winds
6. Validate retrieved fluxes against available standards

Measuring CO_2 from Space

- **Record** spectra of CO_2 and O_2 absorption in reflected sunlight

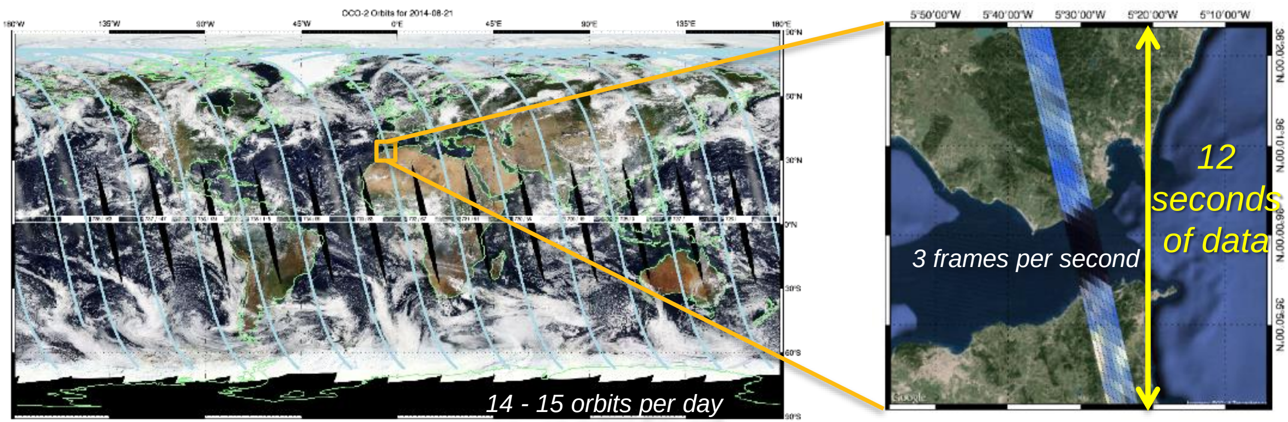


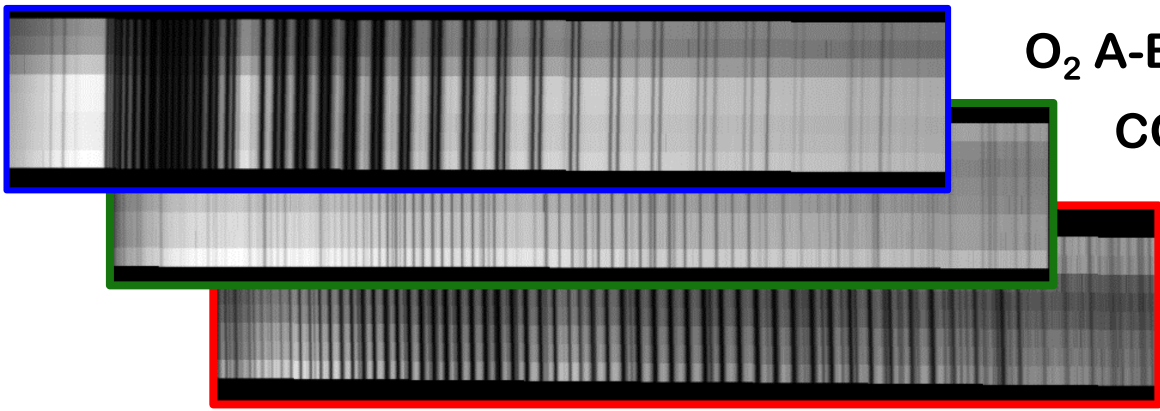
Retrieve variations in the column averaged CO_2 dry air mole fraction, X_{CO2} over the sunlit hemisphere



Validate measurements to ensure X_{CO2} accuracy of 1 ppm (0.25%)

Collecting X_{CO2} Measurements: OCO-2 Sampling Approach





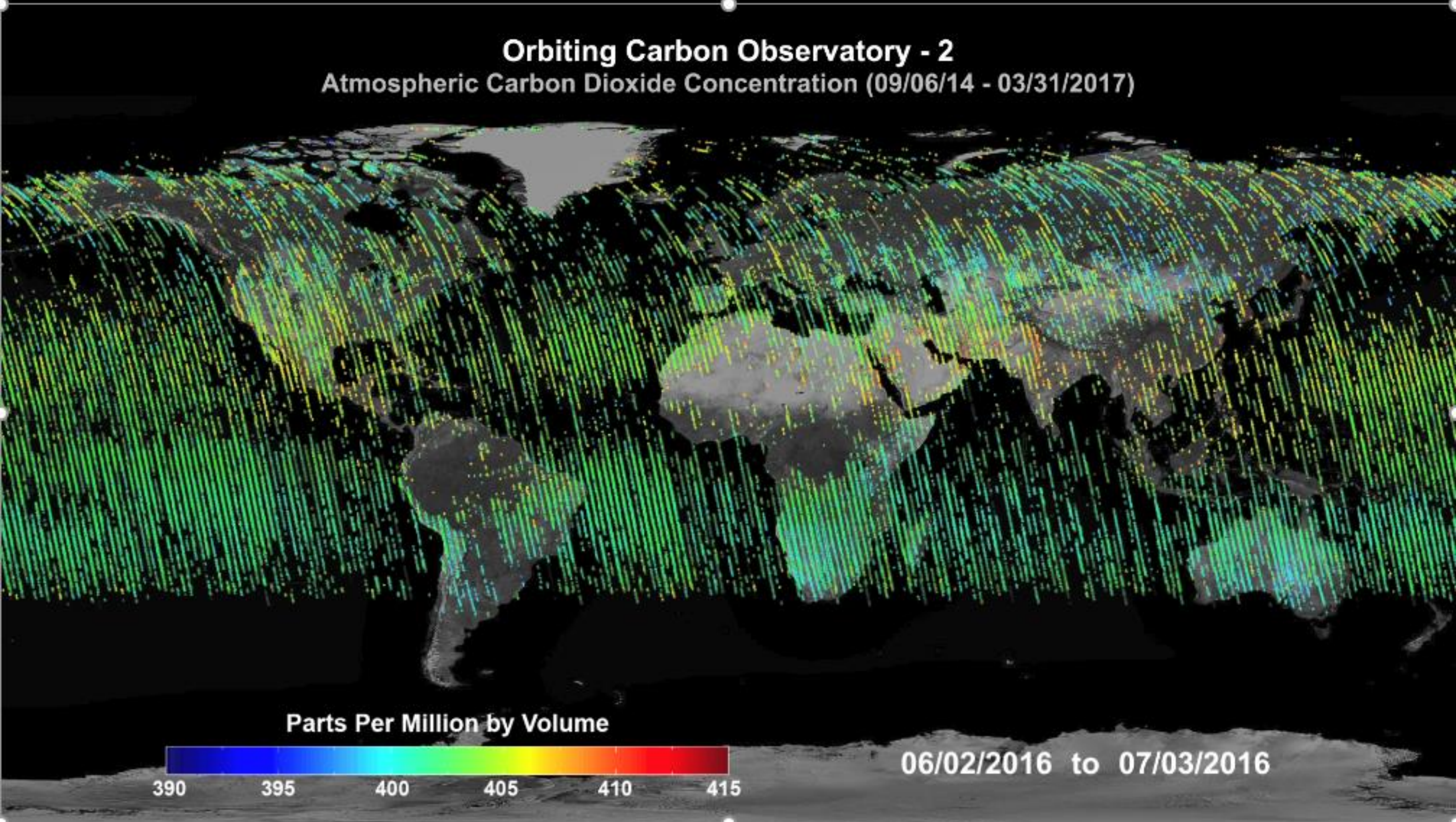
O_2 A-Band

CO_2 1.61 μm Band

CO_2 2.06 μm Band

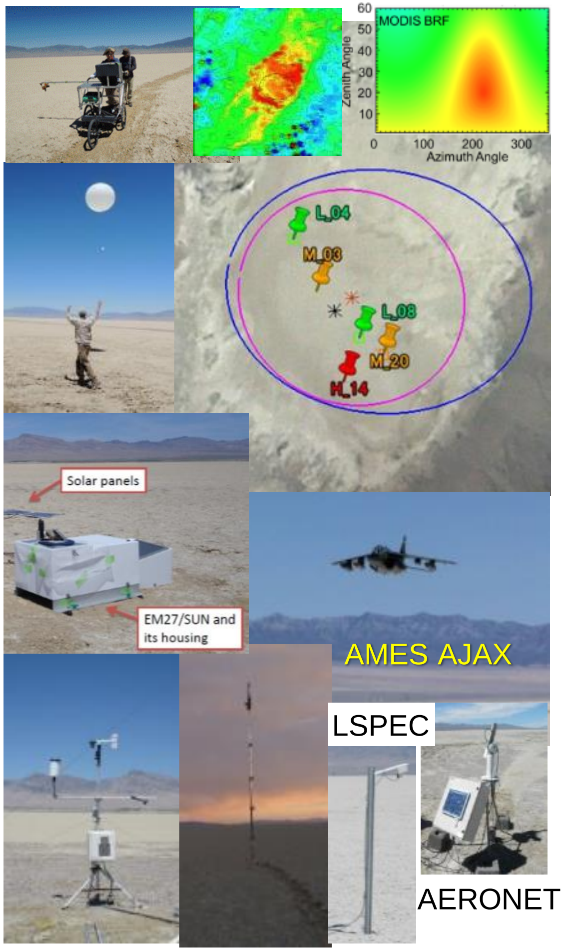
The OCO-2 instrument collects 24 soundings each second as it flies over the sunlit hemisphere of the Earth, yielding almost 1 million soundings each day

A Quick Look at the OCO-2 Prime Mission



Creating a Combined Data Product: the OCO-2/GOSAT Collaboration

Vicarious Calibration



Retrieval Algorithm

Forward Radiative Transfer Model
Spectra + Jacobians

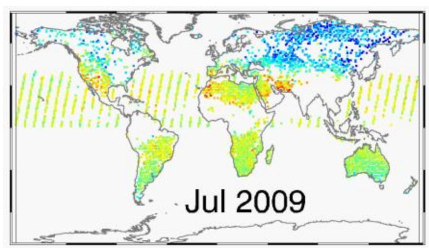
Instrument Model
Spectral+Polarization

Inverse Model
- Compare obs. & simulated spectra
- Update State Vector

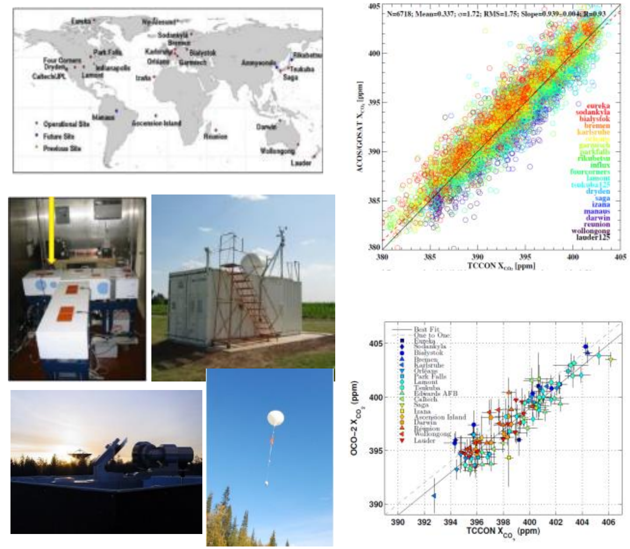
?

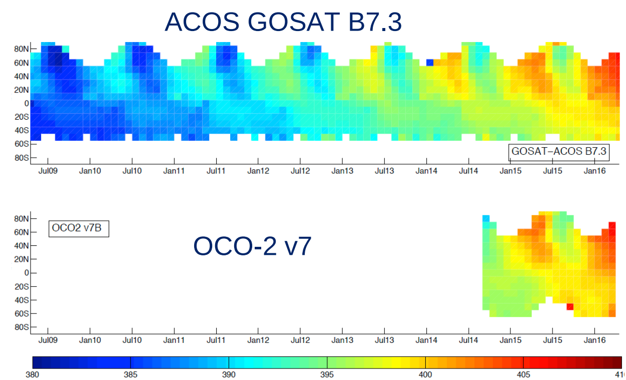
not converged

converged

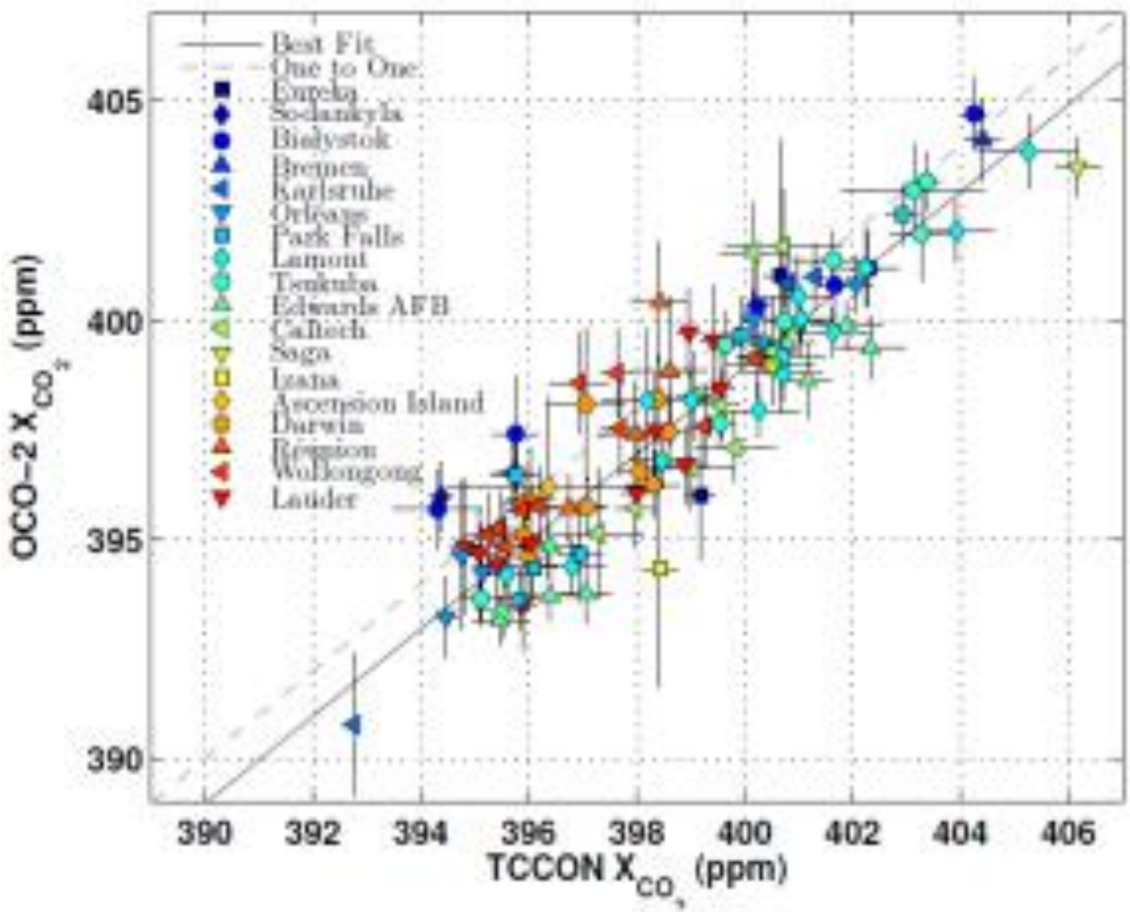


Cross Validation





Validation of X_{CO2} Products Against International Standards: TCCON



Comparisons with the Total Carbon Column Observing Network (TCCON) stations are being used to identify and correct biases in target observations.

After applying a bias correction

- Global bias is reduced to < 1 ppm
- Station-to-station biases reduced to ~1.5 ppm

Wunch et al. (2016)

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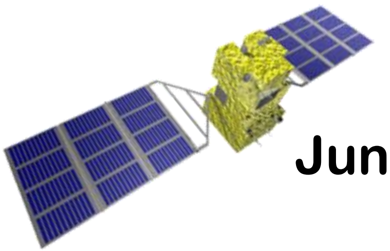
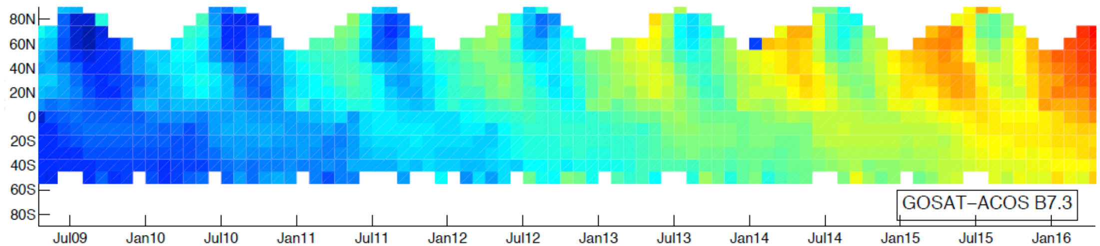
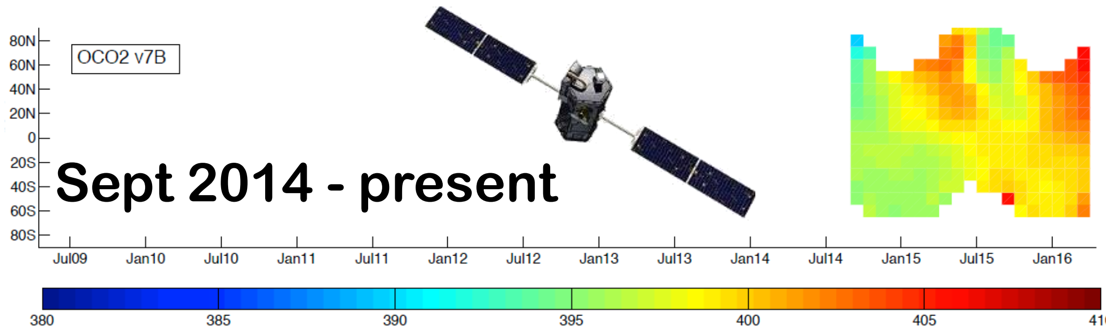
Creating Integrated Data Products: GOSAT and OCO-2



June 2009 - present

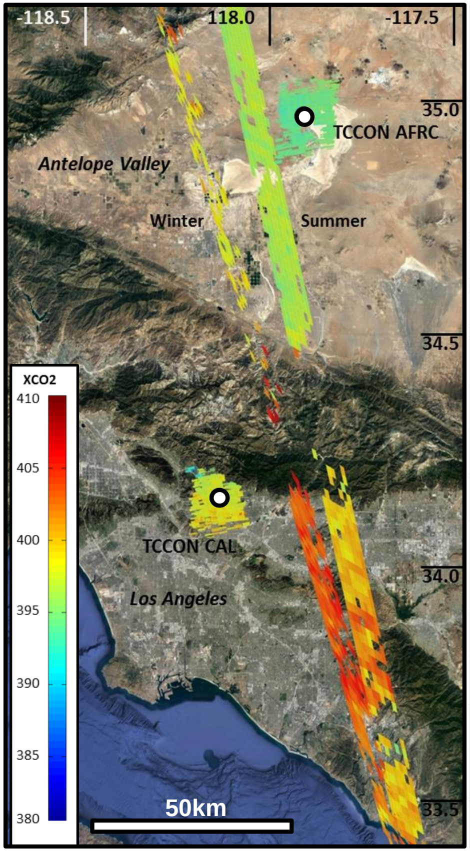




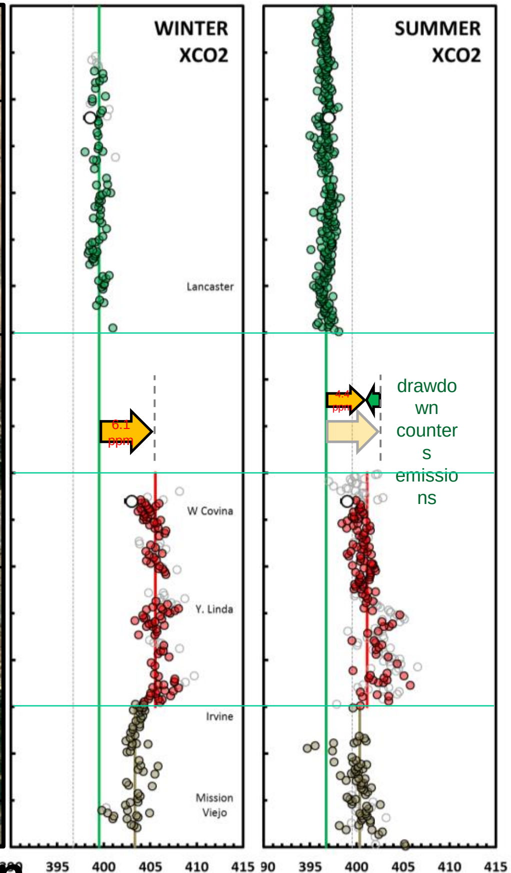
TCCON and other standards have been used to cross validate OCO-2 and GOSAT X_{CO2} to extend the climate data record

- The magnitude of differences between GOSAT-ACOS B7.3 and OCO2 v7r are within ±1 ppm for overlap regions

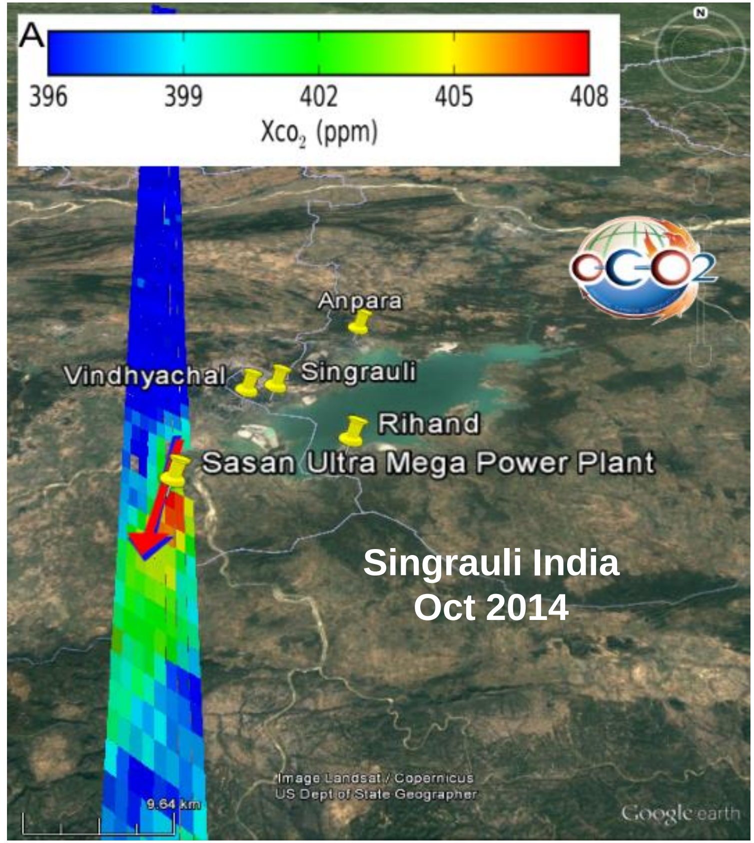
High Resolution and Coverage Needed to Quantify CO_2 Emission Plumes



Los Angeles Basin



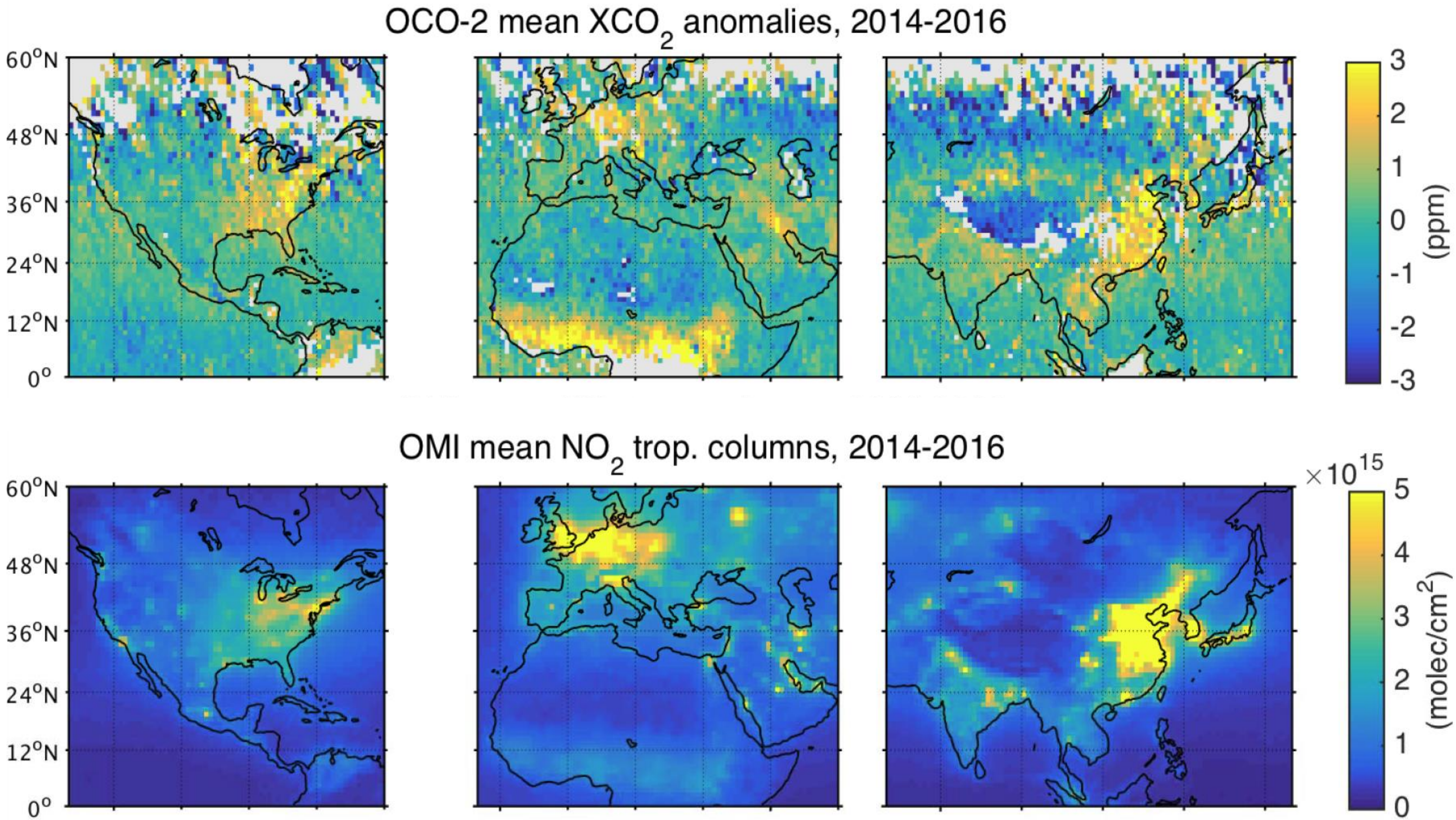
Schwandner et al.(2017)



Nassar et al.(Submitted 2017)

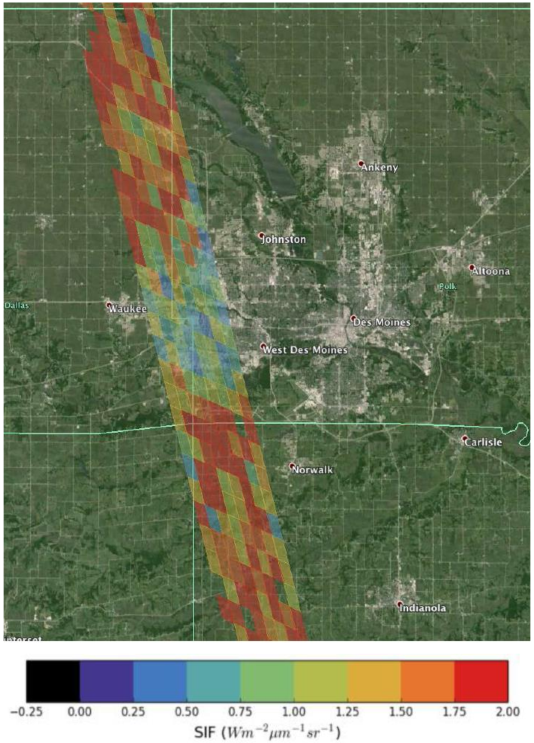
High spatial resolution and full coverage are critical for quantifying localized sources

Proxy Gases are Useful for Tracking and Attributing Anthropogenic Emissions

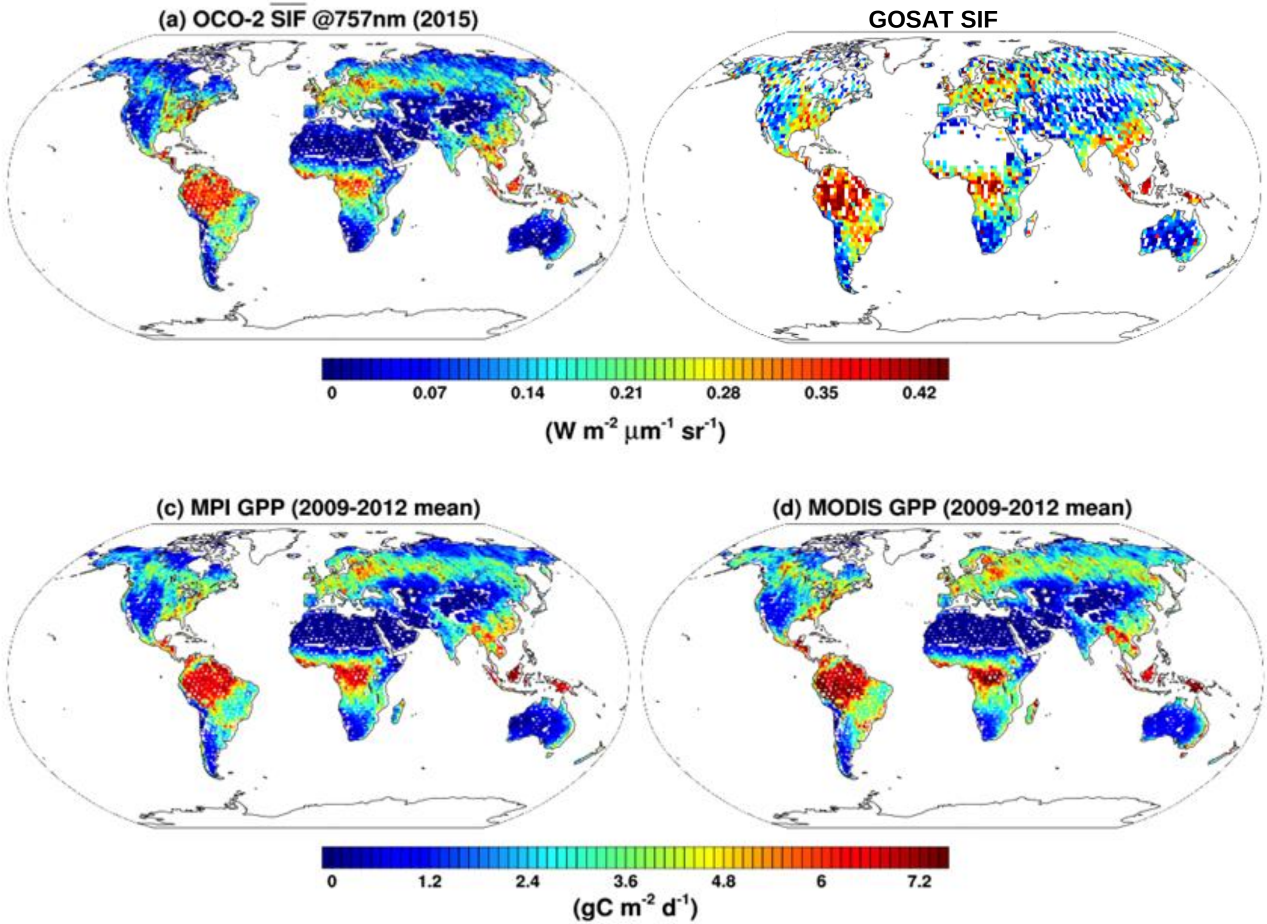


Janne Hakkarainen et al. GRL (2016)

Solar Induced Chlorophyll Fluorescence (SIF) Describes the Role of the Biosphere



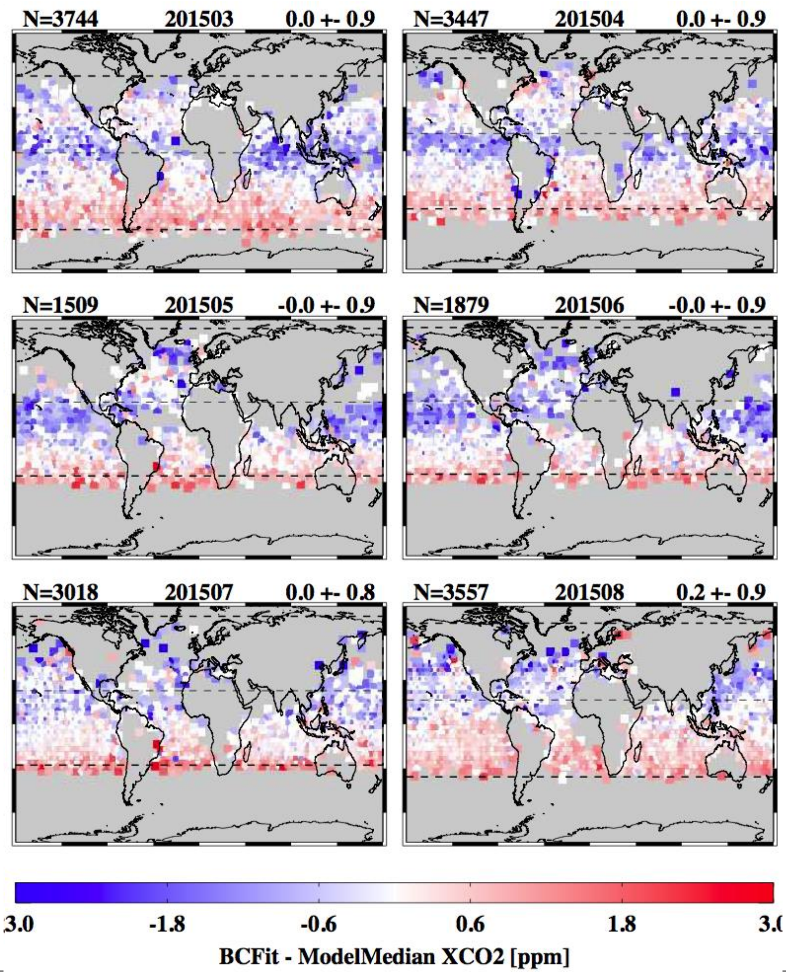
OCO-2 SIF over Des Moines, Idaho



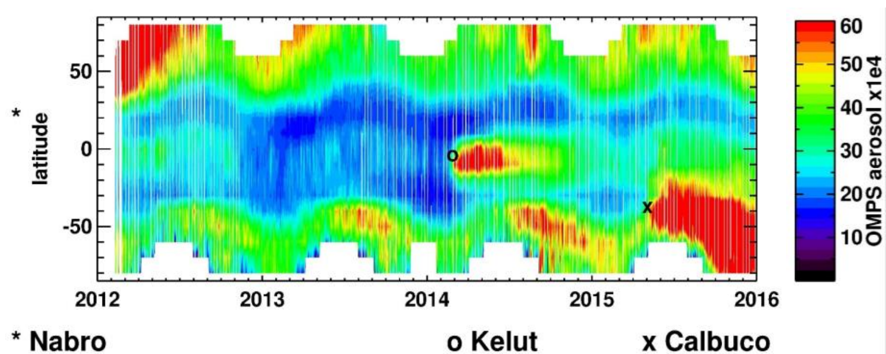
Sun et al. (submitted to Science 2017)

Tracking and Correcting Biases

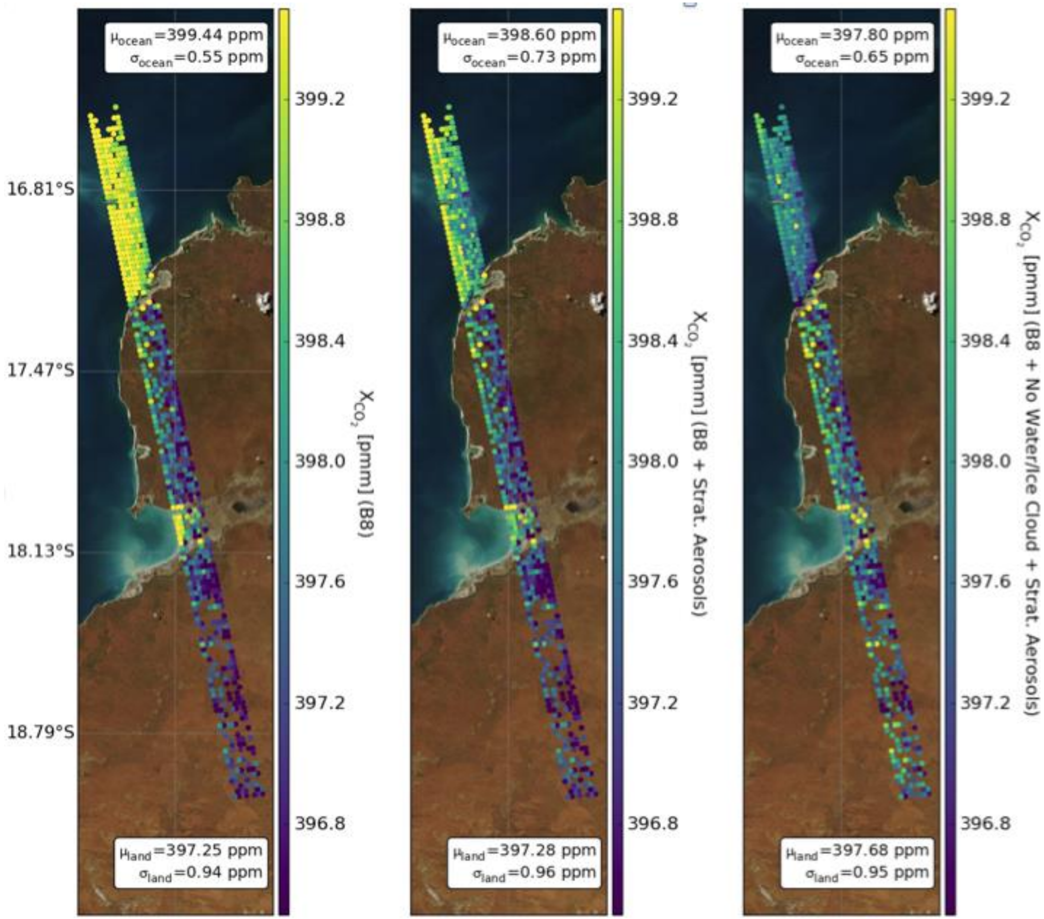
With Strat Aerosols



- High bias seen over southern hemisphere oceans (glint) March-September, relative to models.
- Traced to Optically-thin stratospheric aerosol layers
  - The largest effects are seen at high latitudes over the ocean during the southern winter months
  - Effect was enhanced by volcanic activity (Wolf and Calbuco) which enhanced stratospheric aerosols
- Corrected in the next data product (V8)



Effect on Land/Ocean bias



B7-like B8-like B8-like without water or ice clouds

Rob Nelson, CSU

- **Occasionally, large land-ocean biases appear in the B7 dataset**
- **Left shows a case over NW Australia on Sep 5, 2015.**
- **Mitigated by including stratospheric aerosol (B8-like).**
- **Even better if we remove clouds from retrieval, though we cannot do this in general – sometimes they are needed!**
- **Unclear how to solve this final conundrum**

Coming Attractions: OCO-2 Build 8

- Improved calibration, accounting for ice accumulation and associated zero level offset on 0.76 um O_2 A-band detector.
- Improved Spectroscopy
- Inclusion of Stratospheric Aerosols
- Change from ECMWF to GEOS-5 for prior Meteorology (T, q, surface pressure)
- Improved CO_2 prior
- Improved Land surface reflectance model
- Better pre-screening → more nadir ocean and high-latitude land data.

- Operational processing will begin in late July 2017.

Space-based GHG Measurement Capabilities are Advancing Rapidly

- TanSat Successfully Launched on 22 Dec 2016
- NASA Earth Ventures GeoCarb Selected
- CNES MicroCarb Approved for Implementation

The Role of Space Based Measurements in a Future GHG Monitoring System

- Space based GHG measurements are only one component of the global GHG monitoring system
- Other critical components include inventories, in-stack monitoring, atmospheric observations from ground-based and aircraft monitoring networks, and ground based remote sensing techniques (i.e. TCCON)
- To maximize its utility, the architecture should fully exploit the primary assets of space based remote sensing vantage point
  - Near global coverage of both continents and ocean
  - Adequate spatial resolution to resolve compact sources, such as cities
  - Adequate precision resolve GHG plumes from the background
  - High revisit frequency to resolve temporal changes
- International standards must be defined to cross-calibrate the instruments, characterize the retrieval algorithms, and validate both the X_{GHG} products and flues derived from each observatory to facilitate the integration of results across the constellation

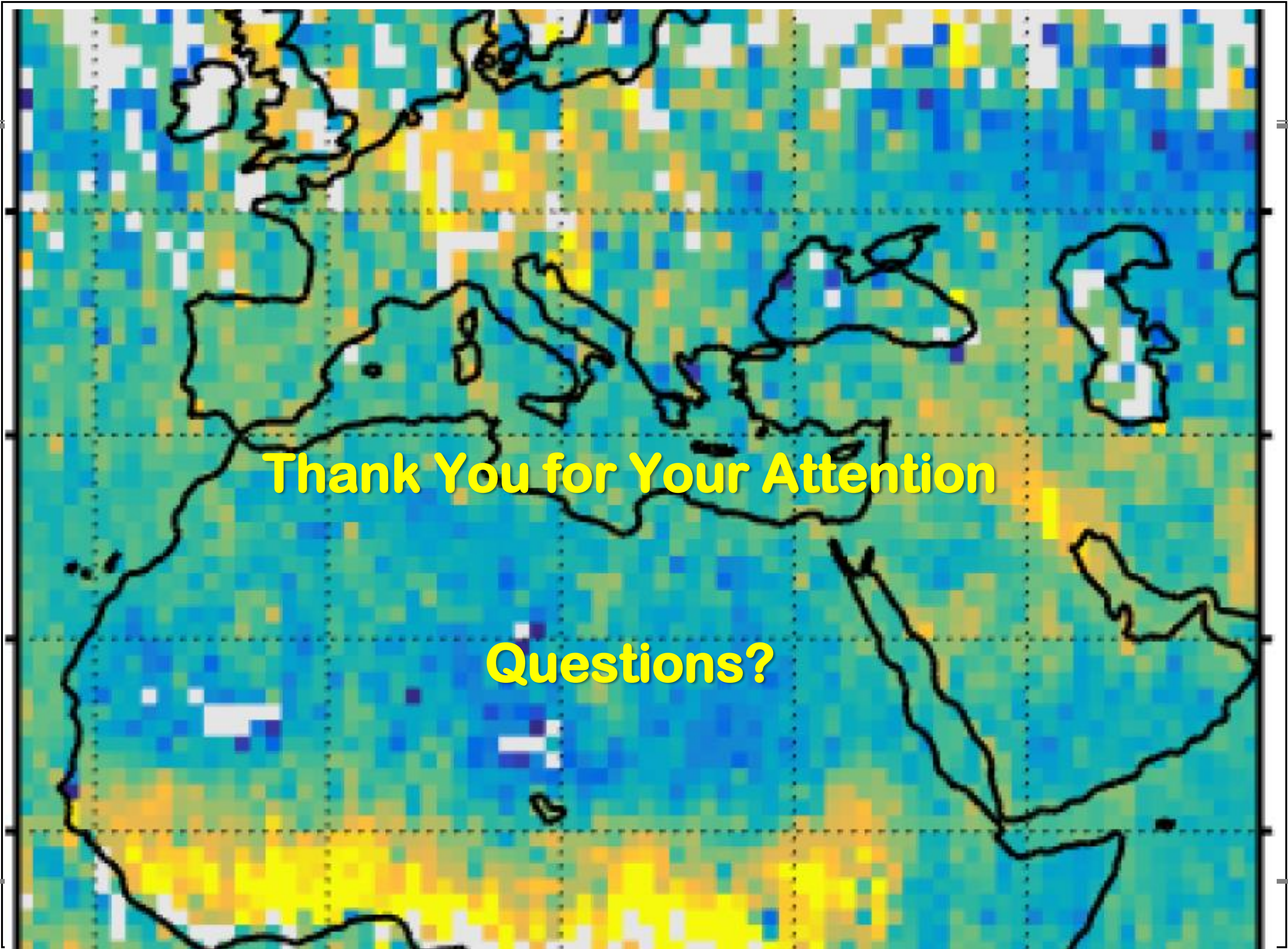
A Candidate GHG Constellation Architecture

The coverage, resolution, and precision requirements could be achieved with a constellation that incorporates the following:

- Coverage and spatial resolution: To cover the globe on bi-weekly intervals, a constellation of ≥ 3 satellites in LEO with
  - Broad (> 200) km swaths with a mean footprint size < 4 km^2
  - Single sounding random error < 0.5 ppm, and vanishing small regional bias (< 0.1 ppm) over > 80% of sunlit hemisphere
  - ≥ 1 satellite with proxy sensors (CO, NO_2, CO_2/CH_4 Lidar)
- Temporal Resampling: Three (or more) GEO satellites to monitor diurnally varying processes over continents
  - Europe/Africa, North/South America, and East Asia
- Infrastructure: A calibration, validation, and flux inversion modeling infrastructure to integrate space and ground based observations to yield reliable GHG fluxes

Summary

- Space-based remote sensing observations hold substantial promise for verifying inventories
  - These data complement existing ground-based and aircraft based in situ data with increased coverage and sampling density
- Over the next decade, a succession of missions with a range of CO_2 and CH_4 measurement capabilities will be deployed
  - These missions are demonstrating the precision and resolution needed to monitor inventories, but improvement in accuracy and coverage needed to for this application
  - Much greater benefits could be achieved if these sensors can be cross-calibrated and their products can be cross-validated so that they can be combined into a long, continuous GHG data record
- Well coordinated constellations of GHG satellites, combined with improved ground and aircraft-based data and flux inversion modeling tools are needed to meet the expanding needs for independent verification of GHG inventories


Thank You for Your Attention
Questions?